Towards Optimal Human-Machine Teaming

Dr. John-Paul Clarke

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Contents

In a human-machine system the “functions of humans and machines are integrated”

– Wikipedia
https://en.wikipedia.org/wiki/Human-machine_system

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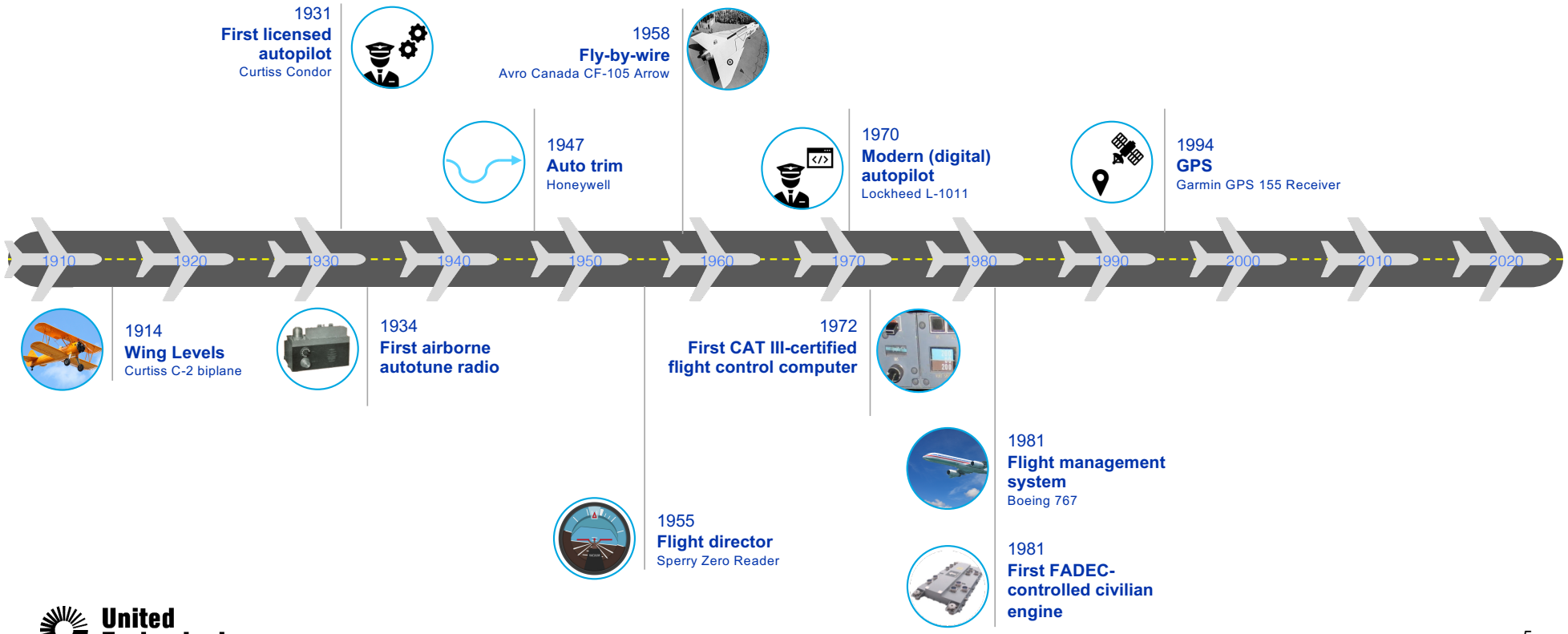
Early human-machine teaming

Women man America's machines in a west coast airplane factory, where the swing shift of drill press operators is composed almost entirely of women., 05/1942

History of automation in aviation



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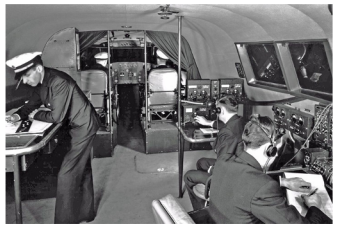
Impact of automation on crew compliment

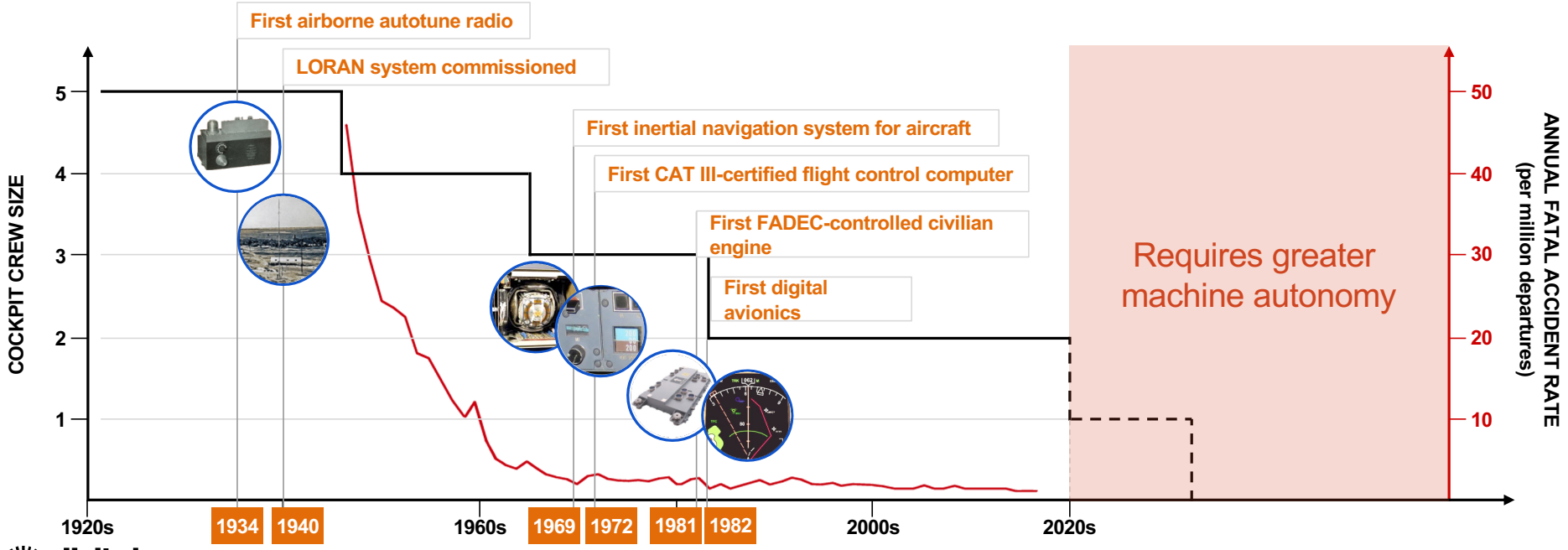

Boeing 314 (5 crew)


Lockheed L-049 (4 crew)


Boeing 727-200 (3 crew)


Boeing 767-100 (2 crew)


Single-Pilot Cockpit (DARPA demo)



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What is autonomy?

- Most people consider a system to be autonomous if it can complete specified tasks without human interaction.
  - System designed to automate a finite set of tasks using predetermined rules, e.g., autopilot, adaptive cruise control, parking, DARPA Robotics Challenge
- This definition implies that the focus of autonomy is on action.

Autonomy is “the quality or state of being self-governing”

– Merriam Webster Online Dictionary
https://www.merriam-webster.com/dictionary/autonomy

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What is self-governance?

- Current view of full autonomy is not self-governance.
  - While they might act/operate independently of other systems or human supervision…
  - operational decisions are made using rules that are prescribed by the designers of the system, and…
  - because of certification requirements, proven to perform in a specific manner under prescribed operating conditions.
- Self-governance requires autonomous decision-making.

How can we tell autonomous decision-making?

Assume someone…

- wakes you up at 3 in the morning,
- describes internal system state and external operating environment, and
- asks you what the system will do…

If you know the answer - Autonomous operation

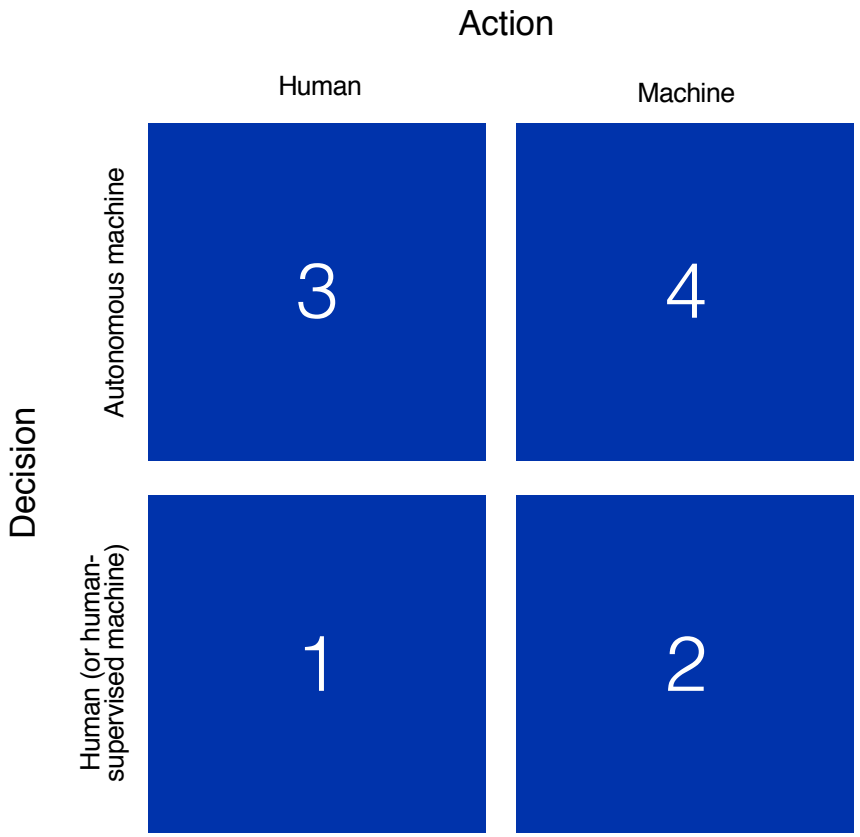
- Decisions prescribed and can be predicted.

If you cannot be 100% certain - Autonomous decision-making

- Decisions cannot be fully predicted despite known parameters.

Alternate view of autonomy

"The Autonomy Quadrant"



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Instance 1

Decision made by Human (or human-supervised machine) + Action executed by human

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Instance 2

Decision made by Human (or human-supervised machine) + Action executed by machine

Instance 3

Decision made by (mostly) autonomous machine + Action executed by human

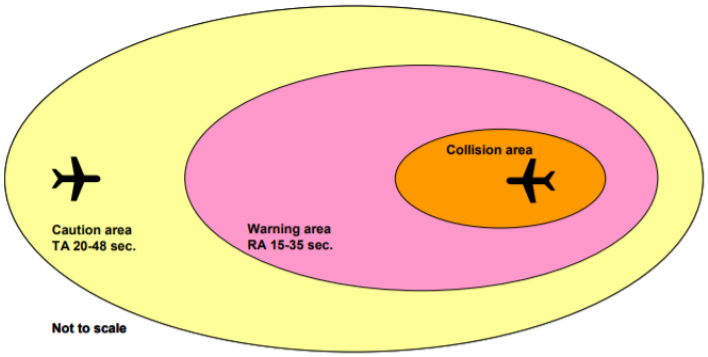

Figure 13: TCAS II protected volume (horizontal view).

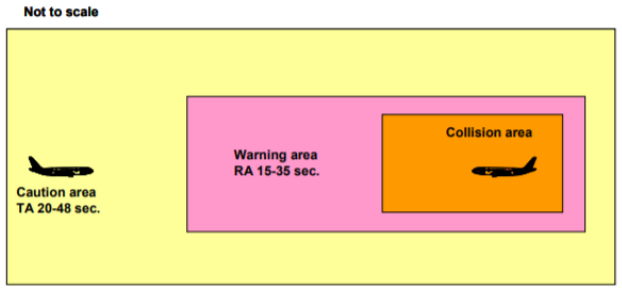

Figure 14: TCAS II protected volume (vertical view).

Instance 4

Decision made by autonomous machine + Action executed by machine

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Certification is a "barrier to increased autonomy in civil aviation"

– Clarke et al.
"Autonomy Research for Civil Aviaiton: Towards a New Era of Flight"
National Academies of Science, Engineering, and Medicine

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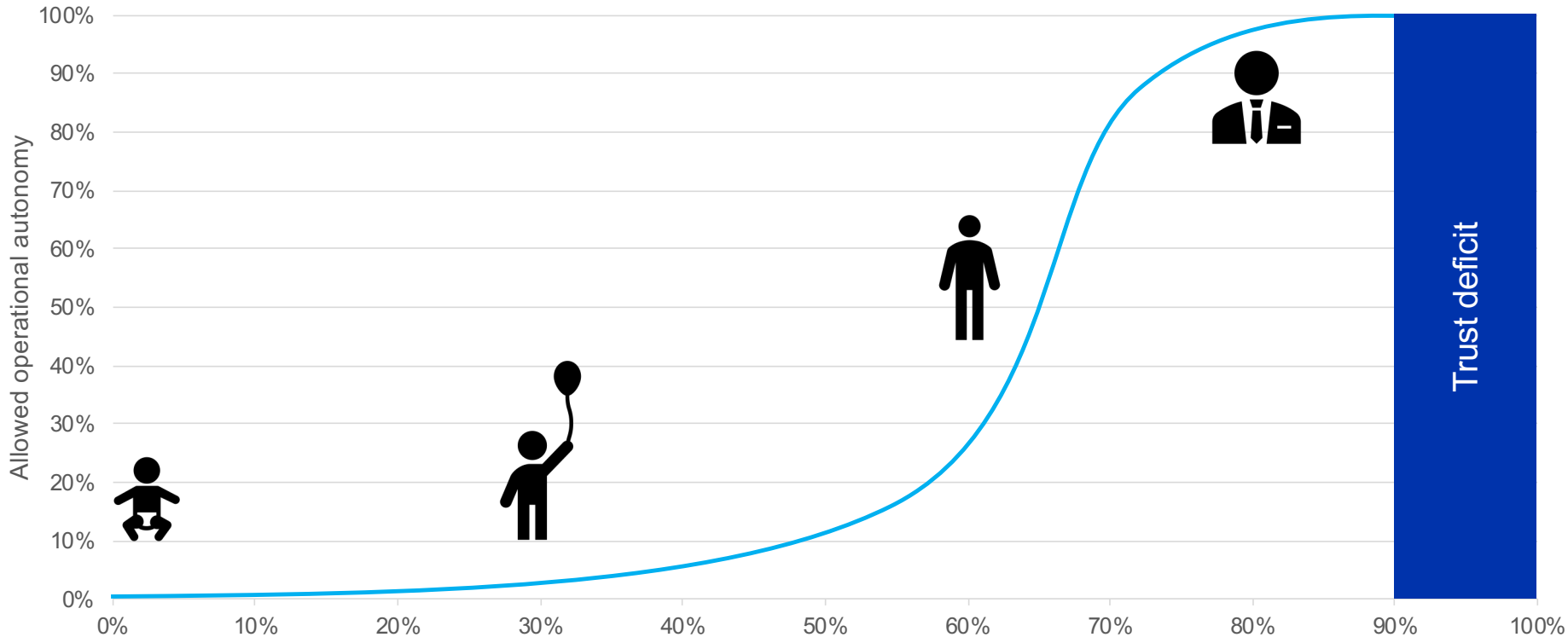
Why is certification of autonomy hard?

- Autonomous decision-making is difficult to certify because…
  - The "real world" is stochastic
  - We cannot enumerate a finite set of operating conditions against which to “prove" the behavior of the system, and…
  - We cannot guarantee that the system will always make the optimal decision, or even a safe decision.
- Are there instructive human-certification examples?
  - Humans are inherently autonomous decision-makers, but...
  - We "certify" humans for various roles and responsibilities based on an assessment of their decision-making abilities.

Parental perspective of human certification

Child v. Teenager v. Adult



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Military perspective of human certification

Private v. Sergeant v. General

Private 

- Very little decision-making autonomy
- Not responsible for the decisions and actions of anyone else.
- Expected to follow orders given by higher ranking authority.

Sergeant 

- Moderate decision-making autonomy
- Responsible for the decisions and actions of small group under their command.
- Expected to make a limited set of decisions and follow orders (but fewer orders) from higher ranking authorities.

General 

- High decision-making autonomy
- Responsible for the decisions and actions of large group under their command.
- Expected to make decisions given objectives from higher ranking authorities.

Aviation perspective of human certification

- We certify pilots every day.
  - We give them licenses based on a check ride.
  - We evaluate them for continued employment and promotion in simulators.
- Why can't we certify autonomous decision-making agents in the same way?
  - What was the flight inspector evaluating when he opened the door of the Cessna 152 during the take-off roll?

Can we a priori measure and build trust in the decision-making ability of a machine?

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An autonomous decision-maker should...

In addition to having clear and measurable objectives...

1. Know itself and its environment
   - Be able to estimate own-system states and the states of the operating environment to a desired level of confidence, i.e., have high situational awareness.
2. Do no harm
   - Only take actions that will result in an outcome that is better than the outcome if no action is taken, i.e., satisfy Hippocratic Oath.
3. Protect itself
   - Only take actions that will keep abilities/capabilities above a minimum threshold.

Could we quantify decision-making abilities a priori?

- Conduct Monte Carlo simulations across a wide range of “representative” scenarios to...
  - Measure the percentage of times that the system correctly estimates its own states and the states of its operating environment.
- Employ sampling-based stochastic programming to determine largest possible...
  - Set of actions that will result in statistically-significant improvements for others relative to no-action, i.e., "no-harm set."
  - Set of actions that will ensure self-state is always statistically-significant better than minimum threshold, i.e., "self-preservation set."

How could we use this information in system design?

- Ensure the machine only picks actions that are in the no-harm and self-preservation sets!
- What should the machine do if there is no single action that is in both the no-harm space and the self-protection space?
  - Is there an appropriate measure of utility?
  - Should legal consequences be a factor?
- This is a question which requires research!

Will people trust autonomy?

"When robots do things we don't understand, like sensing obstacles we can't or following rules we don't know, we tend to lose confidence and wrest control away from them—even when the robots are right."

"Receiving the robot's (simulated) confessions of fallibility allowed the participants to feel more comfort- able balancing their reliance on the machine with their need to jump in"

"After all, a good colleague wouldn't just bail out on a group presentation. Instead, they'd warn you that they tend to stammer and sweat when speaking in front of an audience and then offer to pick up the slack somewhere else."

Anthes, Emily, "You S

Could we use our information to build trust?

- Monte Carlo simulation and stochastic programming results could be used in real time (with current values of state parameters) to estimate and then share confidence estimates in real time with human-agents in the same ways a human would state if asked how confident they were in their solution.

https://www.wired.com/2014/06/trust-robots-2/

How should we allocate roles and responsibilities between humans and autonomous machine?

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"... consider the human agent and the artificial agent in the same way, and the human-machine system as a whole..."

– David Woods, Emilie Roth, & K. Benett (1990). "Explorations in joint human-machine cognitive systems." *Cognition, Computing and Cooperation.*

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Function allocation framework

According to Fitts, 1951 (Human engineering for an effective air-navigation and traffic-control system)...

- Humans are better at:
  - Detecting small amounts of visual or acoustic energy;
  - Perceiving patterns of light or sound;
  - Improvising and using flexible procedures;
  - Storing large amounts of information for long periods and recall relevant facts when appropriate;
  - Inductive reasoning;
  - Exercising judgement.

- Machines are better at:
  - Responding quickly to control signals and applying great force smoothly and precisely;
  - Performing repetitive, routine tasks;
  - Storing information briefly, then erasing it completely;
  - Deductive reasoning and computation;
  - Handling highly complex operations, i.e., performing many tasks simultaneously.

Function allocation framework (cont'd)

According to Feigh and Pritchett, 2014 (doi:10.1177/1555343413490945)...

- Each agent must be allocated functions that its capable of performing, and be capable of performing its collective set of functions;
- The function allocation must be realizable with reasonable teamwork, must support the dynamics of the work, and should be the result of deliberate design decisions.

Function allocation framework (cont'd)

According to Madni and Madni, 2018 (doi:10.3390/systems6040044)...

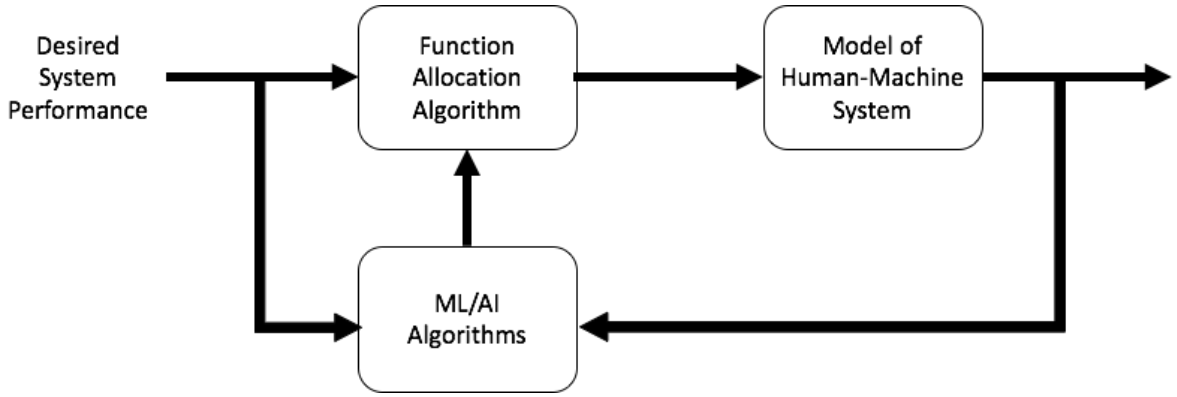
- Agents (human and machine) should be assigned to specific roles in collaborative tasks, and given function and task allocation options for a variety of routine and contingency operational scenarios, as well as conditions/criteria to re-evaluate and change function and task allocations;
- Designers should explore adaptive task allocation schemes to effectively manage human cognitive load, the consequences of what-ifs on human-machine team performance, and innovative machine roles in HMT by exploiting technological advances.
- Designers should also incorporate machine learning methods to continuously improve human-machine team performance.

Function allocation framework (cont'd)

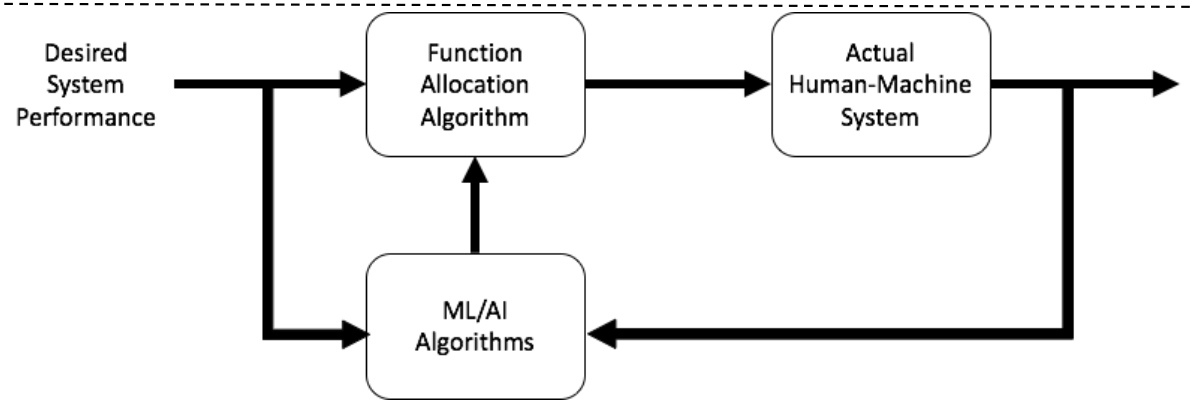
- To consider the human-machine system as a whole, and the human and machine agents in the same way, we need a scalable framework where...
  - The known behaviors of human and machine agents are accurately captured and modeled;
  - The unknown behaviors of human and machine agents can be learned during both design (from simulation) and operation; and...
  - The individual and collective emergent behaviors of all agents can be determined during design via simulation.

Function allocation framework (cont'd)

- During design...



- During operation...



Summary

- In a human-machine system the functions of humans and machines are integrated.
- The future of human-machine teaming requires greater machine autonomy.
- Most people consider a system to be autonomous if it can complete specified tasks without human interaction, but this definition implies that the focus of autonomy is on action.
- Autonomy is the quality or state of being self-governing, and self-governance requires autonomous decision-making.

Summary (cont'd)

- Certification is a barrier to increased autonomy in civil aviation.
- Autonomous decision-making is difficult to certify but there are instructive human-certification examples.
- Humans are certified for various roles and responsibilities based on an a priori assessment of their decision-making abilities.
- An autonomous decision-maker should know itself and its environment, do no harm, and preserve itself.
- Potential to measure decision-making abilities a priori via Monte Carlo simulations and sampling-based stochastic programming.

Summary (cont'd)

- To allocate roles and responsibilities between humans and autonomous machine we must consider the human agent and the artificial agent in the same way, and the human-machine system as a whole.
- There is need a scalable framework where the known behaviors of agents are accurately captured and modeled; the unknown behaviors of agents can be learned during both design and operation; and the individual and collective emergent behaviors of all agents can be determined during design.